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THE TWO-STORE MODEL OF MEMORY: PAST CRITICISMS, CURRENT STATUS, AND FUTURE DIRECTIONS

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SUMMARY

Atkinson and Shiffrin (~~1965,~~ 1968) presented what is now usually referred to as the two-store model of memory. The treatment of this model in textbooks on memory is almost universally based on the assumption that subsequent research has shown that it has serious deficiencies. It is argued that this picture is quite wrong and that the theoretical framework proposed by Atkinson and Shiffrin is in fact quite capable of handling findings obtained within a levels-of-processing framework (Craik & Lockhart, 1972) or the working memory approach (Baddeley & Hitch, 1974).

The SAM theory (Raaijmakers & Shiffrin, 1981) may be viewed as the current version of the two-store model. A general overview is given of the application of this theory to a variety of memory phenomena. Recently, the SAM model has been modified to include the notion of contextual fluctuation (Mensink & Raaijmakers, 1988). This concept, adapted from Estes (1955a,b), refers to the changes in the composition of the set of active contextual elements that occur during retention and/or interpresentation intervals. This notion has proven useful in the application of the SAM model to interference and forgetting phenomena. New research is discussed that extends this model to spacing and repetition phenomena.

Finally, a number of speculative comments are made concerning the integration of semantic memory into the SAM framework and the distinction between implicit and explicit memory.

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Het twee-stadia model van het geheugen: Terugblik, huidige status en toekomstige ontwikkelingen

J.G.W. Raaijmakers

SAMENVATTING

Atkinson en Shiffrin (1965, 1968) presenteerden een algemeen model voor het geheugen dat bekend staat als het "two-store" model. De behandeling van deze theorie in veel handboeken lijkt gebaseerd op de veronderstelling dat later onderzoek gebreken heeft aangetoond in deze theorie en dat alternatieve theorieën zoals de "levels-of-processing" (Craik & Lockhart, 1972) en de "working memory" (Baddeley & Hitch, 1974) benaderingen deze verschijnselen beter kunnen verklaren. Een analyse van de oorspronkelijke "two-store" theorie laat echter zien dat deze kritiek gebaseerd is op een onjuiste interpretatie.

De SAM theorie van Raaijmakers en Shiffrin (1981) kan worden gezien als de huidige versie van het "two-store" model. Er wordt een overzicht gegeven van de toepassing van deze theorie op verschillende geheugentaken. Speciale aandacht wordt besteed aan de recente uitbreiding van de SAM theorie met een model gebaseerd op het begrip contextfluctuatie. Met dit begrip wordt gedoeld op veranderingen in de actuele context gedurende de intervallen tussen studie en test en tussen opeenvolgende leertrials. M.b.v. dit begrip kunnen verschijnselen op het gebied van interferentie, vergeten, en de effecten van spreiding van leertrials worden verklaard.

Tenslotte worden enkele speculaties gemaakt m.b.t. de toepassing van de SAM theorie op het semantisch geheugen en het onderscheid tussen impliciete en expliciete geheugentaken.

1 INTRODUCTION

About 25 years ago, Atkinson and Shiffrin (1965, 1968) presented what is now usually referred to as the two-store model of memory. The two-store model proposed that a distinction should be made between a temporary, Short-Term Store (STS) and a more permanent Long-Term Store (LTS). A basic assumption was that storage of information in LTS is determined by the processing in STS. The Atkinson-Shiffrin model quickly became quite popular and for a number of years dominated the field of memory research. In the early seventies, however, it became clear that a number of phenomena were difficult to explain within this model. These included studies that showed a dissociation between the time that an item resides in STS and the strength of the LTS trace, and studies that showed that recency effects, assumed to be due to STS, could be observed in situations where STS does not play any role. As a result, alternative theories were presented that could handle these findings better, the best known ones being the levels-of-processing framework proposed by Craik and Lockhart (1972) and the working memory model proposed by Baddeley and Hitch (1974).

The above brief historical account, or something quite similar, can be found in many current textbooks on human memory. I will argue, however, that this account is wrong and that current versions of the two-store model are in fact quite capable of handling these apparent difficulties[1]. It is my hope that this will lead to a reappraisal of the two-store model.

Following this reexamination of the two-store model, I will discuss a few aspects of the SAM theory originally proposed by Richard Shiffrin and myself (Raaijmakers & Shiffrin, 1980, 1981). This theory may be regarded as a modern version of the two-store model. I will present some new applications of this model that illustrate its usefulness as a general framework for analyzing memory processes.

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[1]The observation that a levels-of-processing account is quite compatible with a STS/LTS framework has been made several times in the past (see e.g. Bjork, 1975; Shiffrin, 1977), although this does not seem to have had any repercussion on the typical textbook presentation.

2 EVALUATING THE CRITICISMS OF THE TWO-STORE MODEL

2.1 Basic principles of the two-store model

The Atkinson and Shiffrin (1968) version of the two-store model emphasized a distinction between permanent, structural aspects of memory and flexible control processes. Although their description of the structural aspects with the distinction between sensory registers, short-term store, and long-term store, has received most attention, the specification of control processes or strategies of information processing in a precise and quantitative framework was probably much more important in the long run. I will briefly discuss each of these, including the modifications proposed by Atkinson and Shiffrin (1971) and Shiffrin (1975, 1976).

Atkinson and Shiffrin (1968) originally proposed a division of memory into three stores: the sensory registers, short-term store, and long-term store. In more recent versions (Atkinson & Shiffrin, 1971; Shiffrin, 1975, 1976) the sensory registers have been combined with STS into a single component, also termed STS. Furthermore, it is emphasized that STS should not be viewed as a physiologically separate structure. Rather, it should be thought of as the temporarily activated portion of LTS (as in the more recent ACT model, see Anderson, 1976, 1983).

This STS is a kind of working memory that serves the dual purpose of maintaining information in a readily accessible state and of transferring information to LTS. What gets stored in LTS is determined by the type of processing that is carried out in STS, that is, what is stored is what is rehearsed, coded or attended to in STS.

Rehearsal or coding processes in STS are control processes, the nature of which is determined by task constraints, prior experience, etc. Atkinson and Shiffrin (1968) presented a specific quantitative model that incorporated one such control process, termed rehearsal. This so called buffer model was used to give a precise explanation of performance in a particular type of experimental paradigm. One frequent misunderstanding seems to be the idea that this rehearsal buffer is equivalent to STS itself. However, Atkinson and Shiffrin explicitly did not view the rehearsal buffer as a structural aspect of the memory system. Instead they saw the maintenance and use of the buffer as a process entirely under the control of the subject. That is, STS does not consist of a fixed number of slots in such a way that once the

slots are filled STS is full. The buffer model was only a convenient way of modelling the rehearsal process.

Atkinson and Shiffrin made a distinction between two aspects of STS control processes: *rehearsal*, maintaining the information in STS, and *coding*, storing information in LTS. These two aspects, rehearsal and coding, should in most practical situations be regarded as the end points of a continuum: even a "pure" rehearsal process will lead to storage of some information in LTS and a "pure" coding process will similarly keep some of the information in a active state, and hence in STS.

What probably confused many people was that Atkinson and Shiffrin presented in their original paper a model that focused on rehearsal but that did assume some storage in LTS as a function of the length of the rehearsal period. As a result, rehearsal came to be viewed as *the* mechanism for transfer of information from STS to LTS. In later analyses (Shiffrin, 1975), this aspect was clarified by replacing the terms "rehearsal" and "coding" with "maintenance rehearsal" and "elaborative rehearsal", respectively. Maintenance rehearsal has the primary function of keeping the information in a readily accessible state while elaborative rehearsal has the primary function of storing information in LTS.

2.2 The levels-of-processing framework

Craik and Lockhart (1972), in a very influential paper, proposed what they termed "an alternative framework for human memory research". They assumed that memory performance was determined by the level of processing that was given to the to-be-remembered material. They made a distinction between Type-I and Type-II processing. Type-I processing refers to continued processing at the same level that serves to maintain the information in what they termed primary memory. Type-II processing, on the other hand, involves a "deeper" analysis of the information that should lead to improved memory performance.

Their analysis received considerable support from a large number of experiments in which it was shown that simply keeping the information in an active state (Type-I processing) has no effect on recall performance but that the probability of recalling information is strongly influenced by the nature of the processing carried out at the time of initial processing. Even though later experiments showed that Type-I

processing has some effects on long-term storage especially if a recognition measure is used (Dark & Loftus, 1976; Nelson, 1977), this finding that long periods of Type-I processing had little effect on recall performance, was considered by Craik and Lockhart (1972) and others as crucial evidence against the Atkinson-Shiffrin two-store model. Ever since, this conclusion has been echoed over and over again in many review articles (e.g. Postman, 1975; Crowder, 1982; Baddeley, 1983) and textbooks.

However, over the years there have been many instances where this conclusion has been rejected (Bjork, 1975; Glanzer, 1977; Shiffrin, 1977). As I mentioned previously, the two-store model does not assume that every type of rehearsal is equally effective for long-term storage. In fact, the distinction between Type-I and Type-II processing is virtually indistinguishable from the earlier distinction between the control processes of rehearsal and coding, respectively, or maintenance and elaborative rehearsal. Hence, these results by no means invalidate the two-store model. If anything, they provide strong evidence for the role of control processes in memory.

In hindsight, it is difficult to understand why so many researchers have interpreted these results as evidence against the two-store model. This is even more surprising since a casual look at the Craik and Lockhart (1972) paper shows that they did in fact propose a kind of two-store model. That is, they made a distinction between primary and secondary memory, where primary memory has the function of maintaining the information in an active state for further processing. It is unfortunate that proponents of the levels-of-processing framework have never put their model in a quantitative form. I believe that such an exercise would have demonstrated the close similarity of such a model to the two-store model.

2.3 The working memory model

The second criticism that I want to discuss briefly, derives from the work on the working memory model proposed by Baddeley and Hitch (1974). Whereas the levels-of-processing framework focused on the nature of the relation between STS and LTS, the working memory approach entails a detailed analysis of the nature of STS itself. For the present discussion, two types of results are most relevant. The first is that the research carried out in this framework shows that concurrent memory load has a strong effect on the pre-recency part of

the serial position curve but no effect on the recency part. This means that concurrent memory load affects the storage of information in LTS but does not affect the number of items that are retrieved from STS. According to Baddeley and Hitch (1974) this result is inconsistent with the two-store model. Although the exact reasoning has never been spelled out in great detail, the basic idea seems to be that the concurrent memory load should have kept STS fully occupied, leaving little room for the additional items presented on the free recall list.

The second type of result that is thought to be incompatible with the two-store model is the finding that recency effects can also be observed on certain types of long-term memory tasks. This long-term recency effect is interpreted by Baddeley and Hitch (1974, 1977) and others as the result of an ordinal retrieval strategy. Since the two-store model attributes recency effects in free recall to retrieval from STS, it supposedly cannot accommodate long-term recency effects that cannot be assumed to be based on STS.

Let us now take a closer look at these two types of results and their implications for a two-store model. I will argue that these criticisms are based on the incorrect assumption that the rehearsal buffer proposed in Atkinson and Shiffrin's model is a structural aspect of memory and that it is more or less coincident with STS. In their 1971 paper on the properties of the short-term store, Atkinson and Shiffrin already argued that STS and the rehearsal buffer should not be equated. For example, they showed that particular rehearsal strategies did affect the primacy part of the serial position curve but did not affect the recency part. A similar assumption has to be made in order to explain recency effects in single-trial paired-associate recall. In such a paradigm, there is no primacy effect but there is a recency effect (see Murdock, 1974). According to the two-store model the absence of a primacy effect indicates a one-item rehearsal buffer. If the buffer and STS were equivalent, a one-item recency effect would be predicted.

The recency effect is assumed to result from recall from STS, i.e. those items that are still in an active state at the time of recall. Which items are still in STS at the time of recall is determined both by the rehearsal strategy as well as by the forgetting properties of STS. That is, rehearsal may be thought of as having the effect of re-activating an item's representation in STS (Schweikert & Boruff, 1986). If an item is not rehearsed it will take some time before it is

really forgotten from STS. In fact, if every item would be immediately forgotten once attention is taken away from it, it would be difficult to successfully implement a rehearsal buffer strategy.

Consider now the finding that recency is unaffected by concurrent memory load while recall from LTS is. I propose that such a result is not incompatible with a two-store model. To explain such a result, it only has to be assumed that the items do enter STS, even though STS is kept busy by the concurrent memory load. Although the memory load may make it difficult to actively maintain the items in STS (through rehearsal), they do not immediately disappear once the next item on the list is presented. Since the items do enter STS, the recent ones should still be retrievable from STS once recall starts. Is this a likely interpretation for these results? Well, first of all, even the working memory approach has to assume that the items do enter working memory in the first place, otherwise an ordinal retrieval strategy would not work and there would not be any recall possible. Second, the serial position curves presented by Baddeley and Hitch (1974) show some recall for the earlier items, even in the memory load condition. Hence, this is, at least in a two-store model, consistent with the assumption that the task does leave spare capacity for coding processes, and that these items have indeed entered STS.

What about long-term recency effects? The two-store model assumes that in a free recall task the subject first tries to recall those items still in STS. This, to me at least, seems a very sensible strategy. These items are easily accessible and easily lost, so why not recall them right away? This recall from STS leads to a recency effect since the items that are still active in STS most likely come from the end of the list. However, no one would deny that other factors could also lead to a recency effect. For instance, suppose that the items at the end of the list are much easier than the other items. This too would lead to a recency effect. The problem with the criticism based on long-term recency effects is that it makes a logical error. The two-store model assumes that recall from STS leads to recency, or in symbolic form: $A \rightarrow B$. It does not follow that the reverse, $B \rightarrow A$, is also true. That is, the model does not assume that all recency effects are based on recall from STS. In fact, as I will show later, modern versions of the two-store model such as the SAM model, predict that retrieval from LTS is based on contextual retrieval cues. Such contextual retrieval will, everything else being equal, lead to an advantage for more recent items if the context stored in the memory images can be assumed to vary.

This analysis is supported by findings that show that short-term and long-term recency effects are differentially susceptible to the effects of various experimental factors. For example, long-term recency is not sensitive to output order while short-term recency is (Dalezman, 1976; Whitten, 1978). Moreover, interresponse times in regular free recall show an abrupt increase after the first three or four items (see Metcalfe & Murdock, 1981). Although I am not aware of similar data in long-term recency paradigms, I expect that the results will be quite different.

3 THE SEARCH OF ASSOCIATIVE MEMORY THEORY

In the previous sections, I argued that the two-store framework is still viable. This does not mean that there have been no developments since the presentation of the Atkinson-Shiffrin model. One model that may be considered as a contemporary version of the two-store model is the Search of Associative Memory (SAM) theory proposed about a decade ago by Raaijmakers and Shiffrin (1980, 1981). Since that time, this theory has been extended to a large number of memory paradigms, including paired-associate recall, recognition and interference paradigms (Gillund & Shiffrin, 1984; Mensink & Raaijmakers, 1988, 1989).

The SAM theory has given a much more detailed description of retrieval processes in long-term memory. As in the two-store model, it is assumed that during study items are held in a limited-capacity short-term store. Storage in LTS is determined by the nature of the coding processes involved. Retrieval from LTS is based on a cue-dependent search process that takes the limited capacity of STS into account. It is a fairly general framework that may be used to construct more specific models for various experimental paradigms.

3.1 The basic framework

The basic SAM framework assumes that during storage information is stored in what are called "memory images". The information stored includes item, associative and contextual information. The amount and type of information stored is determined by coding processes in STS (elaborative rehearsal). In most intentional learning paradigms the amount of information stored is a function of the length of time the

item is studied in STS. Although retrieval may be also based on STS, in most situations (especially real-life ones) it will be based on LTS.

Retrieval from LTS is based on cues. These cues may be words from the studied list, category cues, contextual cues, or any other type of information that the subject uses in attempting to retrieve information from LTS. Whether or not an image is retrieved, depends on the associative strengths of the retrieval cues to that image. These associative strengths are a function of the overlap of the information in the cue and the information stored in the image.

An important property of SAM is that it incorporates a rule to describe the overall strength of a set of probe cues to a particular image. Let $S(Q_j, I_i)$ be the strength of association between cue Q_j and image I_i. The combined strength or activation of image I_i, $A(i)$, for a probe set consisting of $Q_1, Q_2, \ldots, Q_m$ is given by

$$A(i) = \prod_{j=1}^{m} S(Q_j, I_i)^{W_j} \tag{1}$$

The W_j in this equation are weights assigned to the different cues representing their relative salience or importance. These weights are used to model the limited capacity of STS in retrieval. That is, it is assumed that the sum of the weights is limited (Raaijmakers & Shiffrin, 1981; Gronlund & Shiffrin, 1986): adding extra cues takes attention away from the other cues. The basic aspect however is that a product rule is used to combine the individual cue strengths into a single activation measure. This multiplicative feature focuses the search process on those images that are strongly associated to *all* cues.

3.2 Recall paradigms

In recall tasks, the search process is based on a series of elementary retrieval attempts. Each retrieval attempt involves the selection or sampling of one image based on the activation strengths A_i. The probability of sampling image I_i is equal to the relative strength of that image compared to the other images in LTS:

$$P_S(I_i) = \frac{A(i)}{\Sigma\, A(k)} \tag{2}$$

Sampling of an image allows recovery of information from that unit. For simple recall tasks where a single word has to be recalled, the probability of successful recovery of the name of the encoded word is assumed to be an exponential function of the sum of the weighted strengths of the probe set to the sampled image:

$$P_R(I_i) = 1 - \exp \left[- \sum_{j=1}^{m} W_j S(Q_j, I_i) \right] \quad (3)$$

Special assumptions are necessary when an image has previously been sampled using one or more of the present cues but that recovery was not successful. In that case, recovery is based only on the "new" components of the sum in Eq. (3), corresponding to cues that were not involved in the earlier unsuccessful retrieval attempts (see Gronlund & Shiffrin, 1986).

If the retrieval attempt is successful, the associative connections between the probe cues and the sampled image are strengthened. Thus, SAM assumes that learning occurs during retrieval as well as during study. This assumption leads to a kind of retrieval inhibition since it will decrease the probability of sampling other images. If the retrieval attempt is not successful, a decision is made whether to continue, either with the same set of cues or with some other set of cues. It is usually assumed that the decision to terminate the search process is based on the number of unsuccessful searches although other types of stop rule are also possible.

3.3 Recognition

Although SAM assumes that the process of activating information is basically the same in recall and recognition, there are some important differences. Gillund and Shiffrin (1984) proposed that old-new recognition decisions are based on the overall activation to the probe cues. That is, the overall activation, $\Sigma A(k)$, defines a kind of familiarity value that is used in a signal detection type model to determine the probability of recognition. In order to derive predictions, some assumption is needed about the variance of the strength distributions. Typically, it is assumed that the standard deviation is proportional to the mean strength value (Gillund & Shiffrin, 1984; Shiffrin, Ratcliff, & Clark, 1990).

However, within the SAM framework other types of models are also possible. For example, I believe that it would be worthwhile to consider a model that assumes that recognition is based on a comparison of the overall activation with both context and the item as cues versus the item cue alone. Such an alternative model has not yet been worked out in the SAM framework[2]. For most predictions, this probably would not make much difference. However, it might handle frequency effects in recognition tasks more easily than the Gillund and Shiffrin model.

3.4 The contextual fluctuation model

In applications of the SAM model to typical episodic memory tasks it is assumed that contextual information is always encoded in the memory image and that context is one of the retrieval cues. In the original SAM model, context was used as a means to focus the memory search on the target list of items. Context and changes in context also play an important role in the prediction of forgetting phenomena. There are two basic factors: First, the context cue used after a short delay will in general be more strongly associated to an image than the context cue used after a long delay. Second, the strength and number of other images associated to the context cue may be greater after a long delay. The general assumption here is that the strength of the context cue to an image is based on the similarity of the context at retrieval to the context at storage.

Changes in context may be of a discrete, discontinuous nature or occur in a more gradual way. Discrete changes are typical for studies that explicitly manipulate the test context (e.g. Godden & Baddeley, 1975; Smith, 1979) and may also occur at boundaries between lists, at breaks between study and test periods, and at switches between distinct classes of study items. On the other hand, gradual changes may be assumed when the experimental paradigm is quite homogeneous in character (as in continuous paired associate paradigms or when the length of the retention interval is varied). In such cases, context similarity will be a non-increasing function of delay.

Mensink and Raaijmakers (1988, 1989) recently proposed an extension of the SAM model that was designed to handle such time-dependent changes in context. The new model proposes that changes in context can be

[2]A similar assumption is made by Humphreys, Bain and Pike (1989).

modelled by adopting the notion of fluctuation, as used in Estes' Stimulus Sampling Theory (Estes, 1955a,b). The basic idea is that there is a random fluctuation of elements between two sets, a set of available context elements and a set of (temporarily) unavailable context elements. Performance is a function of the relationship between sets of available elements at different points in time (viz. study and test trials).

In this version of the SAM model, the experimental context is represented as a set of contextual elements. At any given time, only a part of this set is "perceived" by the subject and this subset is denoted the current context. Elements in this set are said to be in the active state. All other elements are inactive. With the passage of time, the current context changes due to a fluctuation process: some inactive elements become active and some active ones will become inactive. At storage only active elements are encoded in the memory image. If there are multiple study trials, each study trial gives a new opportunity for encoding a particular element in the image. The context strength at test is assumed to be proportional to the overlap between the set of context elements encoded in the image and the set of context elements that are active at the time of testing. Mensink and Raaijmakers (1989) show how some simple assumptions concerning the fluctuation process lead to equations that may be used to compute the probability that any given element is active both at the time of storage and at the time of retrieval, and hence the overlap between encoding and test context.

4 A REVIEW OF THE MOST IMPORTANT APPLICATIONS

The SAM theory was proposed as a model that could be used to integrate phenomena from various memory paradigms within a single theoretical framework. The basic idea was that a general quantitative framework could be used to investigate issues and controversies that are difficult to decide without a quantitative formulation. As such, SAM has been quite successful. Quantitative models have been developed for free recall, paired-associate recall, interference paradigms, and various recognition paradigms. In this report I will briefly review these applications, focusing attention on those results that are most intriguing and best illustrate the usefulness of a quantitative framework such as SAM. Special attention will be given to some new

developments relating to the application of the model to spacing and repetition phenomena.

4.1 Free recall

SAM was initially developed as a model for free recall. This application is still one of the most successful ones. Although that model was conceptually simple, it has turned out to be quite complicated in terms of analyzing its predictions. This is because it involves a large number of dependencies that make it difficult to intuit what the predictions of the model will be for a particular experimental manipulation.

Raaijmakers and Shiffrin (1980, 1981) demonstrated that SAM predicts many findings that have been observed in free recall paradigms. One important prediction of SAM is the list-length effect: the longer the list, the lower the probability of recalling any particular item from that list. This list-length effect is predicted because the rules for terminating the search imply that *relatively* fewer samples are made from a longer list than from a shorter list. This phenomenon seems to be a general characteristic of retrieval processes: *the larger the number of items associated to a cue, the smaller the probability that any one of those items will be recalled*. This basic aspect of cue-dependent memory has been termed the *cue-overload principle* and has been used by Watkins to explain a number of empirical phenomena (see Mueller & Watkins, 1977; Watkins, 1975; Watkins & Watkins, 1976). Thus, it is of some interest to note that this cue-overload principle can be derived from the SAM theory.

Probably the most intriguing aspect of the SAM model for free recall was its prediction of the *part-list cuing effect*. This effect refers to the *decrease* in the probability of recall when at test some of the list items are given as cues. This result was surprising since this effect was generally considered problematic for any model that assumes the use of interitem associations in recall. It seemed that giving some items as cues should have aided recall. However, no increase is observed; in fact, most studies show a decrease in recall of the remaining items. Application of the SAM model to this paradigm revealed that the logic underlying this prediction was not correct. Although it is still difficult to pin-point exactly the conditions under which the SAM model will or will not predict a negative effect for part-list cues, we showed that an important aspect has to do with

the nature of the cues used during retrieval. The experimenter-provided cues (used by the cued group) are inferior to self-generated cues because those cues evoke a search-set containing at least one cue item. For the noncued or control condition there is no such bias in the composition of the search-set. Hence, the images sampled by the cued group come from a set that contains relatively fewer target items.

The SAM model is able to explain most of the results that have been obtained in this paradigm (see Raaijmakers & Shiffrin, 1981). We recently completed a study in which the SAM explanation for the part-list cuing effect was tested against a class of theories that attribute the negative cuing effect to storage factors (e.g. Roediger & Neely, 1982). In this study, subjects were presented lists of unrelated words. They were tested either immediately or after a delay filled with learning a list of paired associates. The SAM model predicts that the usual negative effect will be obtained in the immediate recall condition but that a positive effect will be obtained in the delayed testing condition. The reason for this prediction is that the part-list cues will benefit in conditions where subjects are not able to recall many items without any cues. On the other hand, most other explanations of the part-list cuing effect that attribute the effect to storage factors, predict that the effect should be the same for both immediate and delayed testing. The results (see Fig. 1) supported the SAM model: there was a negative effect of cuing in the immediate condition and a positive effect of cuing in the delay condition.

What is perhaps the most significant aspect of the model concerning these cuing results is that the model is able to predict with essentially the same mechanism both the negative part-list cuing effect as well as the large positive cuing effects that are obtained when the list is composed of a number of categories and the subject is given the category names as cues. In such a paradigm, cuing has a positive effect because the cues are optimally related to the associative structure; that is, the subject is given one good cue from each of the clusters.

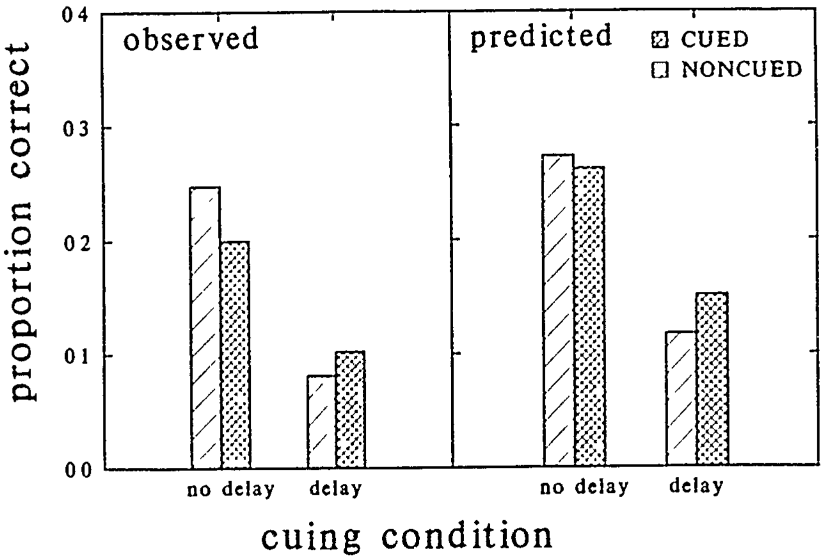

Fig. 1 Proportion correct in free recall, with and without part-list cues, for immediate and delayed testing. The left panel gives observed data from an unpublished experiment; the right panel gives simulated results from the SAM model for free recall.

4.2 Recognition

Gillund and Shiffrin (1984) presented a detailed analysis of the SAM model for recognition. As mentioned earlier, the model assumes that a simple yes/no recognition decision is not based on the retrieval of specific episodic images but on the overall activation of LTS in response to the cues. Depending on the experimental paradigm, these cues are the context cue and the tested item or pair of items.

Of particular interest for a general memory model like SAM is whether the model is able to handle differences and similarities between recall and recognition. Gillund and Shiffrin showed how a number of such results could be explained within the SAM framework. They showed that the model can handle (1) the similar effects of list length, (2) the finding that maintenance rehearsal has little effect on recall but does have an effect on recognition, (3) the result that elaborative rehearsal has an effect on recall but little effect on recognition, (4) the observation that changes in context between study and test have a negative effect on recall but no effect on recognition, and (5)

the differential effects of natural-language word frequency on recall and recognition.

Recently, attention has been drawn on what has been termed the "*list-strength effect*" (Ratcliff, Clark, & Shiffrin, 1990; Shiffrin et al., 1990). This refers to the effects of strengthening (or weakening) some list items upon memory for other list items. Ratcliff et al. (1990) show in a series of experiments that strengthening some items on the list has a negative effect on recall of the remaining list items but has no or even a positive effect on recognition performance. This stands in contrast to the list-length effect: adding items to a list decreases both recall and recognition performance.

In a prototypical experiment on the list-strength effect, three conditions are compared: a pure list of weak items (e.g. brief presentation time, single presentation), a pure list of strong items, and a mixed list consisting of both weak and strong items. The typical result is that strong items do better than weak items, both in pure and mixed lists. This holds for recall (especially free recall) and recognition testing. However, the critical aspect is that recognition performance on strong items in mixed lists is not better than in pure lists. Similarly, weak items are not recognized worse on mixed lists than on pure lists. This is surprising since we know that adding items to the list harms performance so one would also expect an effect of the strength of these other items.

Shiffrin et al. (1990) show that this intuitive reasoning is indeed correct. They examined a large number of current models (including SAM, MINERVA 2, and composite, distributed memory models such as holographic, matrix, and various types of connectionist or neural net models), and show that all of these models in their current form cannot predict both the presence of a list-length effect and the absence (or reversal) of a list-strength effect. They also looked at possible variants of these models. They showed that a variant of the SAM model could handle the results. A variant of the MINERVA 2 model could also be made to handle the recognition results but has some difficulties dealing simultaneously with the recall data.

The "trick" in both models is basically the same. First, one has to assume that different items are stored in separate traces but that repetitions of an item within a list are stored in a single memory trace (under the conditions of these experiments). Second, the variance of activation of each separate trace, when the cue item is unre-

lated to the item(s) encoded in the trace, is constant regardless of the strength of the trace. Finally, it has to be assumed that recall and recognition operate differently, recognition being based on the combined activation of all traces and recall based on access to a single trace.

The first and third of these assumptions do not pose a problem for the SAM model. In fact, I will show in a later section that the assumption that repetitions are often stored in a single trace is also necessary to handle certain data on the spacing of repetitions. The problematic assumption is the second one. In the SAM model for recognition (Gillund & Shiffrin, 1984) the variance of the activation for an unrelated item was assumed to increase with the strength of the context association. Since the interitem associative strength for unrelated items was always set equal to a constant residual value (d), the combined variance for such unrelated items is larger for the stronger items. Shiffrin et al. (1990) propose that the residual strength is not a constant but decreases as a function of the strength of the image. Although this assumption seems ad hoc, it can be defended using a *differentiation* argument: the better the image was encoded, the more clear are the differences between it and the test item, and hence the lower the activation. In this way, a constant or even a decreasing variance may be predicted depending on the weighting of context and item cues.

A crucial aspect of this explanation of list-strength effects is that repetitions of an item are stored in a single memory image. Murnane and Shiffrin (1989) tested the corollary that a reversal of the list-strength effect in recognition will occur if repetitions are presented in such a way that they will be encoded in separate images. They showed that repetitions of words in different sentences produced a list-strength effect whereas repetitions of entire sentences did not. This demonstrates that the nature of the encoding of a repeated item is a crucial factor.

Clearly, what is needed at this time is a more detailed model of how the associative strength of an item cue to an image is determined by the relation between the information in the cue item and the stored image, not only for items not studied together but also for items that were studied together. In addition, some of the older analyses should be repeated to see whether the predictions are still the same.

4.3 Interference and forgetting

Mensink and Raaijmakers (1988) presented an application of the SAM model with the contextual fluctuation assumption to a number of classic findings on interference and forgetting. Most of these findings can be handled in a very straightforward way, including a number of results that were problematic for classical interference theories. For example, suppose two lists of pairs are learned in succession, both with the same stimulus terms but with different response terms (an A-B, A-C paradigm). We showed that the model predicts both retroactive and proactive interference (i.e. a decrease in recall of B and C, respectively, compared to a control condition), even when the subject is asked to try to produce the responses associated with each of the two lists (termed MMFR testing). The occurrence of proactive interference on such a test has always been especially problematic for traditional interference theory because it assumed that such a test was not affected by response competition. To explain the retroactive interference, it had to be assumed that second list learning led to unlearning of the first list associations. This however could not explain the observation of proactive interference on a MMFR test. The SAM model does not have this problem since it predicts that "competition" (in this model due to the fact that sampling is influenced by other images) will not be eliminated by MMFR testing. We also showed that the SAM model could predict appropriate negative and positive transfer relations and some typical results of single-list forgetting paradigms.

One aspect of the SAM model that turns out to be crucial in many of the predictions is the assumption that recall performance is based on both the relative as well as the absolute strengths of the memory images. In the SAM model, the sampling process is a function of the relative strength of the target image compared to the other images, whereas the recovery process is a function of the absolute strength. For example, if one equates recall in the interference and control conditions by giving the interference condition more study trials, this does not imply that the respective associative strengths are also equal. Instead, the model predicts that if the probability of recall is equalized, the absolute strength will be higher in the interference condition and hence the relative strength lower (otherwise recall would not be equal). This result enables us to predict a number of results including the differential effects of interference on accuracy and latency measures (Anderson, 1981).

4.4 Spacing of repetitions

Recently, this model has been used to explain results concerning the spacing of repetitions. Suppose an item is presented twice for study (P_1 and P_2, resp.) and tested at a later time T. If the retention interval (i.e., the interval P_2-T) is relatively long, the probability of recall increases as a function of the spacing between the two presentations (the interval P_1-P_2). With short retention intervals, however, the probability of recall decreases as a function of the spacing between the presentations. With intermediate retention intervals, the results are more complicated, often showing a nonmonotonic effect of spacing.

Recent work by Raaijmakers and van Winsum-Westra shows that this complicated state of affairs is predicted by the SAM model. This is for a large part due to the assumptions concerning contextual fluctuation. As the spacing interval increases, the context at P_2 will include more new, not yet encoded, elements that may be added to the memory image. Encoding more elements in the image increases the expected overlap between the test context and the contextual elements in the image.

Although the basic principle is quite straightforward, the actual model requires supplementary assumptions that complicate matters. Crucial in this analysis is what happens on the second presentation, P_2. It is assumed that on P_2 an implicit retrieval attempt is made for the image stored on P_1 (a study-phase retrieval assumption). New context elements that are present on P_2 are only added to the image formed on P_1 if that image is successfully retrieved on the second presentation. If it is not retrieved, a new storage attempt is made, based only on the information present on P_2; if the attempt succeeds a new image is stored. In addition, in order to accommodate dependencies due to differential storage strengths, it is assumed that each storage attempt is either successful or not. If it is not successful, the probability of sampling that image on a future retrieval attempt is zero. It is further assumed that no new storage takes place for any item that is still in STS on P_2.

In this model, spacing of repetitions has a number of effects. As mentioned, due to context fluctuation more new context elements are stored provided the item is "recognized" on P_2. Second, as the spacing interval increases, there is a corresponding decrease in the probability that the item is still in STS on P_2. Both of these effects lead to

an increase in the probability of recall at test. However, spacing also has a negative effect. The longer the spacing interval, the lower the probability that the image is successfully retrieved on P_2. This is a simple forgetting effect: as the interval increases, the expected overlap between the context at P_1 and that at P_2 decreases and this implies a decrease in the strength of the context cue at P_2. Together, these factors produce a nonmonotonic effect of spacing. The spacing function shows an initial increase followed by a decrease, the maximum point depending on the length of the retention interval (P_2 to T).

The present model has been successfully used to fit the results of a number of well-known experiments (e.g. Glenberg, 1976, Rumelhart, 1967; Young, 1971). In a large study, Glenberg (1976) varied both spacing and retention intervals. Fig. 2 shows the observed data and the predictions obtained with the SAM model.

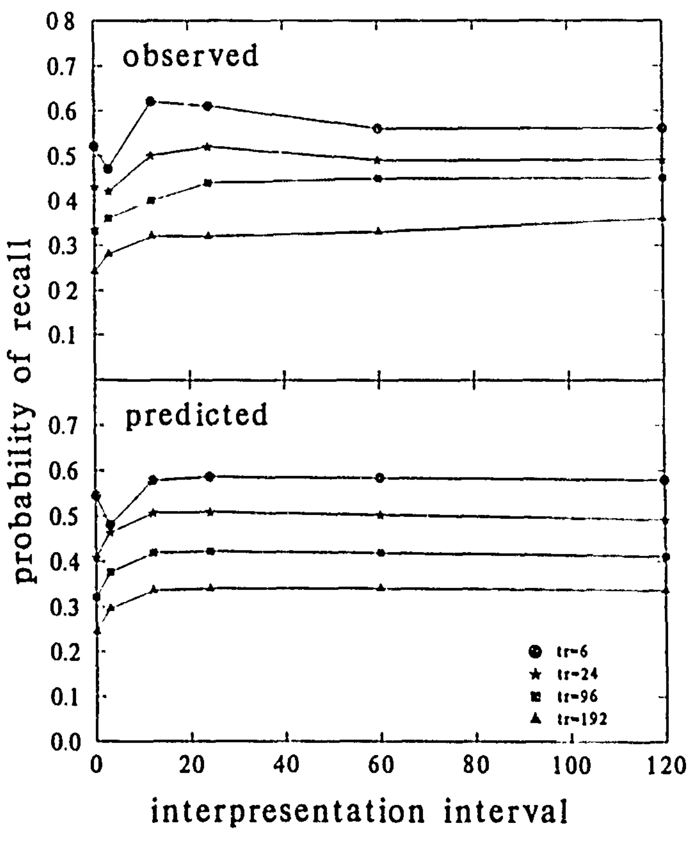

Fig. 2 Observed data (Glenberg, 1976 - top panel) and predictions of SAM (lower panel) for probability of recall as a function of interpresentation and retention (tr) interval (in seconds).

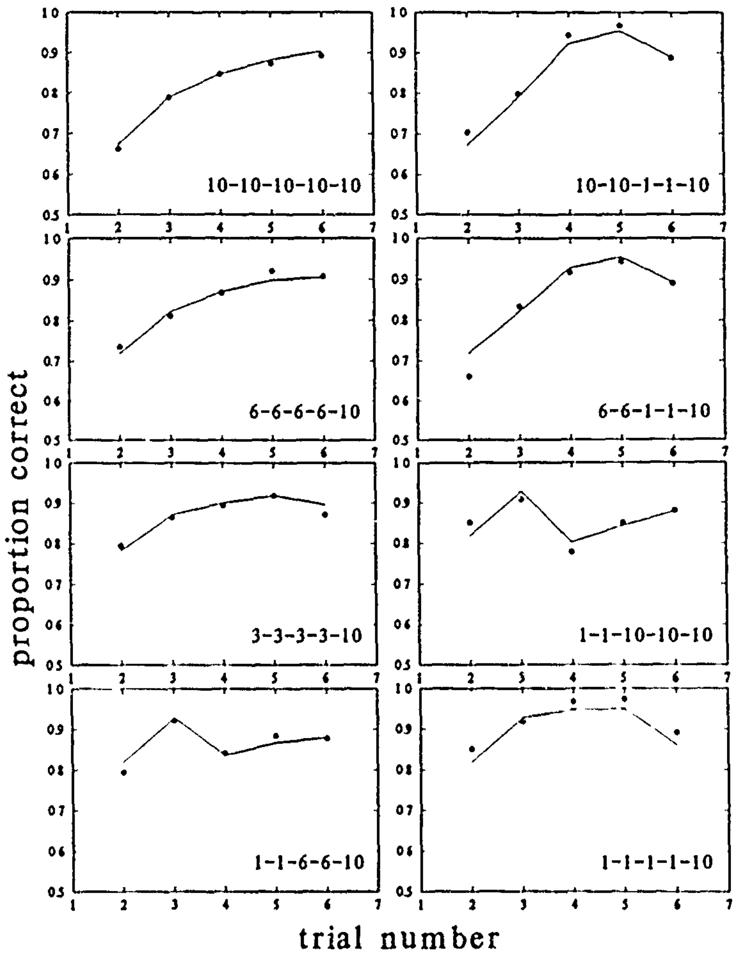

Fig. 3 Observed (dots) and predicted (lines) probabilities of recall for Experiment I of Rumelhart (1967). Numbers in graphs give the spacing (in terms of the number of intervening items) between successive presentations.

We have also fitted this model to the results of a multitrial learning experiment reported by Rumelhart (1967) in which the spacing between the repetitions was varied (see Fig. 3). These results demonstrate that SAM can handle the basic learning data that were the main focus of the Markov models of the sixties.

A particularly interesting aspect of the present model is that it provides an explanation for the intriguing results of Ross and

Landauer (1978). According to their analysis, most theories that explain the effects of spacing by some sort of encoding or contextual variability assumption, predict that there should not only be a beneficial effect of spacing for two presentations of the same item but also for two presentations of two different items. That is, there should be an effect on the probability of recalling either of the two items. They showed that such a result is not obtained: a typical spacing effect is only obtained for one item presented twice, not for two items each presented once.

The present model can handle this result because it treats these two situations quite differently. For the one item case, it predicts that new information is often added to the same memory trace (if the item is recognized). In the two item case, it predicts that two different images are formed.

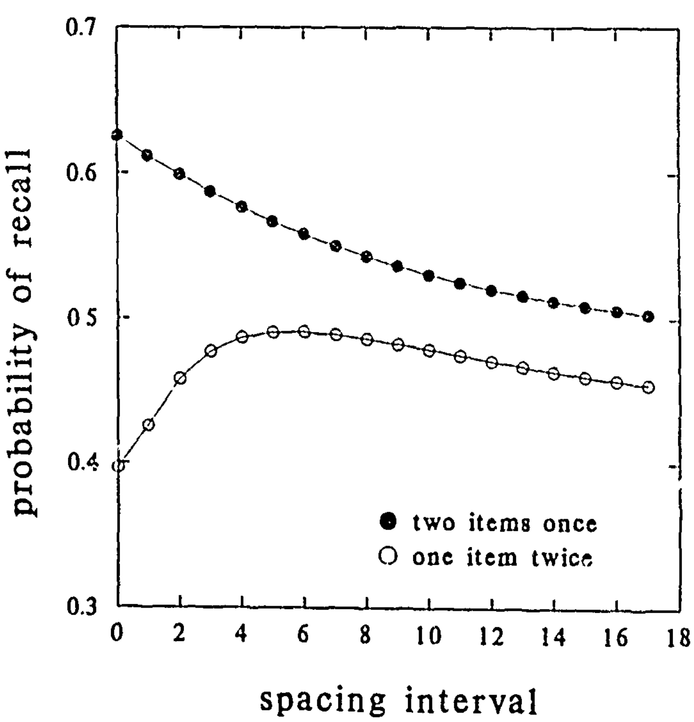

Fig. 4 SAM predictions for the probability of recalling one or both of two items each presented once and for the probability of recall of a single item presented twice, as a function of the spacing interval (in terms of the number of intervening items) between the two presentations. Parameter estimates and experimental design are based on the application of the SAM model to the experiment of Young (1971).

Since recall depends on the overlap in elements with each image separately, the spacing of the presentations by and large only matters for the single item case. This is illustrated in Fig. 4 that shows predicted patterns of results for these two types of items.

It is evident that to explain these results, it is necessary (at least within the SAM framework) to assume that repetitions of an item are often encoded in the same memory image. This conclusion that we have also used in the analysis of interference data, agrees with one of the assumptions that Shiffrin et al. (1990) have found necessary to account for the list-strength effects in recognition. The fact that the same assumption is needed in quite different applications, provides additional evidence for it.

The above account of spacing effects is in many respects quite similar to the Component-Levels theory proposed by Glenberg (1979), although he did not present a quantitative analysis. Interestingly, Glenberg and Smith (1981) mention the Ross-Landauer result as the one result that the Component-Levels theory cannot explain. Our quantitative analysis of the SAM model shows that their conclusion may not have been correct and that their theory can probably handle more data than they are aware of.

5 SOME IMPORTANT THEORETICAL ISSUES

These various applications show that the SAM model is a quite powerful framework for analyzing memory experiments. Perhaps the most significant aspect of a model such as SAM is that it provides a tool for the analysis of various complex and/or problematic memory phenomena. We have found the SAM framework to be fairly easy to work with in this respect. Quantitative predictions for specific designs can be obtained quite easily and such analyses may lead to novel insights into the conditions under which particular phenomena are obtained. This has been true for example in the case of the part-list cuing effect, the list-strength effect, various interference results, and the Ross-Landauer results for spacing of repetitions.

Even though the theory has been applied to many results in the memory literature, there are still a number of issues that will have to be dealt with. In this final section I will discuss a few of these for which there are some preliminary ideas.

5.1 The nature of the units of memory

The first issue concerns the nature of the units in memory. In the original SAM model for free recall it was assumed that the units in memory, the memory images, corresponded to single words presented on the list. However, the SAM theory does not restrict images to single words. Indeed, in the recent models for paired-associate recall, we have assumed the images to correspond to the word pairs presented on the list. This problem of the nature of the units in memory is not unique to the SAM theory. Other theories (e.g. TODAM, MATRIX, neural net models, etc.) will also, at some time, have to consider this issue.

In principle then, the theory is quite unrestricted with respect to the nature of the memory images. Does this mean that there is complete freedom to choose whatever units that one likes? The answer is, not surprisingly, no. There are a number of constraints that follow from the functional rules in the SAM theory. These constraints are (see Raaijmakers & Shiffrin, 1981; Shiffrin, Murnane, Gronlund & Roth, 1989):

1) An image is unitized in the sense that the encoded information can be recovered from that image without further sampling.
2) Information encoded in other, nonsampled images does not contribute to the recovery process.
3) To recover the core information in another image than the sampled one, requires that image to be sampled on a subsequent retrieval attempt.

The general SAM framework assumes that what gets stored in LTS is what is attended to in STS. A corollary of this assumption is that the nature of the units is determined by the nature of the coding processes in STS. For example, if the subject focuses on sentences, the units might be sentences, whereas if the focus is on single words, the memory images would correspond to words. This does not deny that the images themselves might be structured in some way. For example, if the images correspond to sentences, a complete theory might specify how specific words are retrieved from that image. However, the important aspect is that such a retrieval is assumed to be qualitatively different from the retrieval of the image itself. In SAM, retrieval of information from within an image is part of the recovery process and is independent of the information in the other, nonsampled memory images.

Shiffrin et al. (1989) describe some experiments that were designed to investigate the nature of the units in memory when subjects are presented at study with sentences and cued at test with some words from those sentences and asked to recall the remaining words. In their analysis, they not only investigated the nature of the units in storage but also the nature of the units in retrieval. That is, just as the nature of the stored images is determined by the nature of the encoding processes, the nature of the cues that are used during retrieval is also dependent on the way the cue information is encoded. The data clearly favoured a model that posits the use of sentence--level units in storage and retrieval.

5.2 Semantic memory

As shown in this report, the SAM theory has been applied to the major episodic memory paradigms. What has not yet been done, is a specification of how the framework would handle retrieval from semantic memory (e.g. in word association tasks). Although a completely worked out model has not yet been developed, I would like to propose some ideas that may serve as a useful starting point for such an analysis.

The basic idea is that semantic memory represents the accumulation of a large number of specific episodic memories. That is, an episodic memory image is characterized by the inclusion of contextual information. Recalling a particular episodic image requires the use of an appropriate context cue. However, if a particular association is stored in a large number of different contexts, its retrieval will become more or less independent of any specific contextual retrieval information. Hence, it will acquire "semantic" properties. Thus, a semantic association is not stored as one very strong image, but is represented by a large number of images. This idea implies that the semantic-episodic distinction is viewed as a continuum, with some associations being completely context-bound, some completely context-free, and others in between. The extent to which an association is context-free would in this view be determined not just by the total number of times it has been stored but mostly by the total number of different contexts in which it has been stored.

Retrieval of such a semantic association would be context-free in more than one sense. First, it would tend to become activated irrespective of the particular context at the time of retrieval. Second, even when context is not used as a cue, such associations would still be acti-

vated since in that case the retrieval probability would depend simply on the relative number of images (more accurately, the strengths of those images) that incorporate this association as opposed to other associations to the cue item.

Such a model for semantic memory may be used to answer a criticism raised by Humphreys, Bain and Pike (1989) against a number of memory models including the SAM model. This has to do with the so called "*crossed associates*" problem. Briefly, this refers to the fact that experiments show that subjects do not suffer from overwhelming interference when presented with a paired associate list containing, in different pairs, semantic associates. For example, the subject might study pairs such as *bread-queen* and *king-butter*. Humphreys et al. (1989) assumed that SAM could not handle this result because it would predict the retrieval of *butter* in response to the cue *bread* since *butter* is strongly associated to both the context and the item cue.

This is not correct, however. The basic reason is that in SAM cues are associated to images, not to more or less abstract (semantic) representations of individual words. There are two cases that should be distinguished. One is where each image corresponds to a single word. We assume that semantic memory consists of a large number of episodic images. The cue *bread* will be associated to a number of images containing the word *butter*. This holds whether or not *butter* was on the list. If the pair *king-butter* was on the list, a new image containing *butter* will be formed. The cue *bread* will not be strongly associated to this image since the image contains no interitem information containing both *bread* and *butter*. However, even if the subject thinks of *bread* when the pair *king-butter* is studied, this will not be a strong association and hence, the cue will not strongly activate the *butter* image on the list. What is important is that the SAM model does not assume a single memory representation for *butter*. The strong pre-experimental association between *bread* and *butter* is not due to one strong link between *bread* and *butter* but to the fact that both items have co-occurred many items and this information is reflected in a large number of images.

The other case is where each image corresponds to a pair of words. This is the usual assumption in SAM for lists of paired associates. In this case, the cue *bread* is associated to a number of pre-existing images containing both *bread* and *butter* but not to the experimental image representing the pair *king-butter*. The result is that SAM does

not predict strong interference. The explanation by SAM is in this case basically the same as that of Humphreys et al. (1989).

5.3 Implicit memory

Another aspect that we have not yet dealt with, is the rapidly growing literature on "implicit memory". One approach that might prove fruitful to explore, is based on the notion that tasks may differ in the extent to which retrieval relies on the use of context cues. This idea, that is similar to the approach taken by Humphreys et al. (1989), assumes that in implicit or indirect memory tasks, subjects do not rely to any great extent on the use of specific contextual cues.

Even though context is not explicitly used as a cue, recent exposure to an item may still have an effect on the probability of retrieval on a subsequent implicit memory test. One interesting finding is this area has been that certain types of amnesic patients that show little or no memory on an explicit memory task, perform quite well on an implicit memory task. Such results might be explained by assuming that amnesics are impaired in the use of context information in their retrieval. This implies that they will show impairments on explicit memory tests but much less on implicit testing since on such tests both amnesics and normal subjects do not explicitly use contextual retrieval cues.

This assumption that these tasks differ in the type of cues that are used in retrieval, also explains why performance on these tasks will be largely independent, i.e. show a dissociation. Such a dissociation is to be expected whenever different, independent, probe cues are used (as in the recognition failure paradigm).

6 CONCLUSION

The results that I have considered in this report show that the SAM theory provides a useful framework for the analysis of memory phenomena. Since SAM is based on the general two-store framework described by Atkinson and Shiffrin (1968), this demonstrates that the two-store model is far from obsolete as suggested by some critics (e.g. Crowder, 1982). Instead, I believe that that model still provides a very useful framework within which more elaborate models may be formulated.

What strikes me in the literature concerning the issue of the two-store model, is that the distinction between a temporary capacity-limited memory (called active memory, working memory, or STS) and a more permanent memory is an almost universal aspect of contemporary models of memory, even in those models that claim to be alternatives to a two-store model. The reason for this might be that the distinction between STS and LTS is ultimately not based on some kind of questionable dissociation logic but on the (apparent?) necessity of making such a distinction in formulating an information processing model of memory.

Finally, it should perhaps be mentioned that the predictions of the SAM model are in most cases not unique. Other quantitative models may lead to quite similar predictions. Such equivalent predictions should not be interpreted, however, as a weakness of the quantitative approach to memory. Rather, the functional similarity of many current memory models is a manifestation of the growth in our basic knowledge about memory processes, and hence a sign of real cumulative progress.

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The two-store model of memory: Past criticisms, current status, and future directions

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

Atkinson and Shiffrin (1965, 1968) presented what is now usually referred to as the two-store model of memory. The treatment of this model in textbooks on memory is almost universally based on the assumption that subsequent research has shown that it has serious deficiencies. It is argued that this picture is quite wrong and that the theoretical framework proposed by Atkinson and Shiffrin is in fact quite capable of handling findings obtained within a levels-of-processing framework (Craik & Lockhart, 1972) or the working memory approach (Baddeley & Hitch, 1974).
The SAM theory (Raaijmakers & Shiffrin, 1981) may be viewed as the current version of the two-store model. A general overview is given of the application of this theory to a variety of memory phenomena. Recently, the SAM model has been modified to include the notion of contextual fluctuation (Mensink & Raaijmakers, 1988). This concept, adapted from Estes (1955a,b), refers to the changes in the composition of the set of active contextual elements that occur during retention and/or interpresentation intervals. This notion has proven useful in the application of the SAM model to interference and forgetting phenomena. New research is discussed that extends this model to spacing and repetition phenomena.
Finally, a number of speculative comments are made concerning the integration of semantic memory into the SAM framework and the distinction between implicit and explicit memory.

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